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TITLE

Long-distance quantum communication

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The invention relates to the scheme and method for entanglement-based quantum communication protocols, such as quantum teleportation and quantum cryptography.

DESCRIPTION OF THE BACKGROUND

All current proposals for implementing quantum communication are based on photonic channels. The degree of entanglement generated between two distant quantum systems coupled by photonic channels decreases exponentially with the length of the connecting channel due to optical absorption and noise in the channel. Purification means regaining a high degree of entanglement. See Bennett, C. H. et al. Purification of noisy entanglement and faithful teleportation via noisy channels. Phys. Rev. Lett. 76, 722-725 (1991). Exponential decay of entanglement as a function of channel length requires an exponentially increasing number of partially entangled states to obtain one highly entangled states.

The concept of quantum repeaters has been proposed to overcome the difficulty associated with the exponential fidelity decay. See Briegel, H.-J., Duer, W., Cirac, J. I. & Zoller, P. Quantum repeaters: The role of imperfect local operations in quantum communication. Phys. Rev. Lett. 81, 5932-5935 (1991). A quantum repeater using a cascaded entanglement purification protocol for communications systems was proposed in Knill, E., Laamme, R. & Zurek, W. H. Resilient quantum computation, Science 279, 342-345 (1998) and Preskill, J. Reliable quantum computers, Proc. R. Soc. Lond. A 454, 385-410 (1998). This proposed quantum repeater includes many short segments, with the length of each segment comparable to a channel attenuation length. The proposed quantum repeater is used by first generating entanglement and purifying the entanglement for each segment; the purified entanglement is then extended to a longer length by connecting two adjacent segments through entanglement swapping, and so on. Each entanglement swapping decreases the overall entanglement therefore requiring a large number of iterations for sufficient purification.

The inventors recognized that, to implement the quantum repeater protocol, one needs to generate entanglement between distant quantum bits (qubits), store them for sufficiently long time and perform local collective operations on several of these qubits. The inventors recognized that the requirement of quantum memory is essential since all purification protocols are probabilistic. The inventors recognized that, when entanglement purification is performed for each segment of the channel, quantum memory can be used to keep the segment state if the purification succeeds and to repeat the purification for the segments only where the previous attempt failed. The inventors recognized that this is essentially important for polynomial scaling properties of the communication efficiency since no available memory would require that the purifications for all the segments succeed at the same time, and the probability of such event decreases exponentially with the channel length. The inventors recognized that the requirement of quantum memory implies that local qubits be stored in atomic internal states instead of the photonic states, since it is difficult to store photons. The inventors recognized that, if atoms are the local information carriers it would be difficult to implement quantum repeaters, since the prior art indicates that would require strong coupling between atoms and photons with high-finesse cavities for atomic entanglement generation, purification, and swapping. See also Cirac, J. I., Zoller, P., Kimble, H. J. & Mabuchi, H. Quantum state transfer and entanglement distribution among distant nodes in a quantum network, Phys. Rev. Lett. 78, 3221-3224 (1997), Enk, S. J., Cirac, J. I. & Zoller, P. Photonic channels for quantum communication, Science 279, 205-207 (1998). Strong coupling technology does not appear to be feasible.

SUMMARY OF THE INVENTION

It is an object of the invention to provide for entanglement generation with built-in entanglement purification between two atomic ensembles.

It is an object of the invention to provide for entanglement generation with built-in entanglement purification between multiple atomic ensembles.

It is another object of the invention to provide long quantum communication distance.

It is another object of the invention to provide for quantum teleportation, cryptography, and Bell inequality detection.

It is another object of the invention to provide a quantum communication

system having built in entanglement purification and intrinsic fault tolerance.

It is another object of the invention to provide a quantum communication system in which resources scale polynomially with transmission distance.

It is another object of the invention to provide a quantum communication system relying upon collective excitations for entanglement of quantum systems.

The objects of the invention are provided by a system and method comprising generating pulses of light in a pulsed source of light, wherein each pulse of light includes at least one photon; propagating a first pulse of light generated in said pulsed source of light into a first ensemble having a first collective excitation state, wherein photons in said first pulse of light have an energy that can excite said first collective excitation; propagating a second pulse of light generated in said pulsed source of light into a second ensemble having a second collective excitation state, wherein photons in said second pulse of light have an energy that can excite said second collective excitation; receiving from said first ensemble and said second ensemble at an interferer for interfering light pulses substantially only photons resulting from generation of said first collective excitation and said second collective excitation; and receiving at a first single photon detector and second single photon detector light pulses from said interferer propagated to said interferer from said first ensemble and said second ensemble. Additional aspects of the system and method include controlling photon detection of said first single photon detector and said second single photon detector with a photo detector controller; preventing photons not resulting from generation of collective excitations in one of said first ensemble and said second ensemble from reaching said interferer with a first filter disposed between said first ensemble and said interferer; preventing photons not resulting from generation of collective excitations from reaching said interferer with a second filter disposed between said second ensemble and said interferer; wherein an incident photon in a pulse of light generated by said source of light and transmitted into either said first ensemble or said second ensemble has a substantial probability of interacting with the ensemble to generate a collective excitation in the ensemble; wherein said ensemble comprises solid matter; wherein said ensemble comprises gaseous matter; wherein said ensemble comprises liquid matter; wherein said collective excitation of a photon in said pulses of light interacting with one of the ensembles to generate one of the collective excitations defines a Stokes process; wherein each of the ensembles have substantially identical collective excitation energies; wherein said first ensemble

and said second ensemble comprise alkali atoms; wherein said first ensemble and said second ensemble comprise Cesium atoms; wherein a density of Cesium atoms in each one of said first ensemble and said second ensemble is between 1 and 100 atoms per cubic micro meter; wherein said preventing photons not resulting from generation of collective excitations in one of said first ensemble and said second ensemble from reaching said interferer comprises a wavelength sensitive first filter disposed between said first ensemble and said interferer; wherein said source comprises a synchronizer for synchronizing transmission from said source of two pulses; wherein said source comprises a laser; wherein said source comprises a flash lamp; wherein said first ensemble and said second ensemble contain molecules each of which has a collective excitation; ceasing generating pulses of light in said pulsed source of light when one of said detectors detects a pulse; entangling a third ensemble with a fourth ensemble, each having a collective excitation state, wherein photons in said first pulse of light have an energy that can excite said collective excitation state; entangling said first and second ensembles with said third and fourth ensembles; entangling comprises detecting a pulse propagated through a second beam splitter to one of a third single photon detector and a fourth single photon detector; filtering pulses transmitted towards said second beam splitter; entangling said third and fourth ensembles with fifth and sixth ensembles; repeated applications of the basic steps for entanglement with additional sets of ensembles to provide long distance quantum communication in which resources only scale polynomially with the communication distance; repeated applications of the basic steps for entanglement with additional sets of ensembles to provide long distance entanglement generation comprising in which resources only scale polynomially with the communication distance.

In a preferred embodiment, objects of the invention are provided by an apparatus comprising a pulsed source of coherent or incoherent light, two cells with alkali (Lithium, Sodium, Potassium, Rubidium, Cesium, Francium) atoms gas samples (atomic ensembles), two filters, two channels, a beam splitter, two single photon photo detectors. Additional elements of the apparatus include the electronic control system for the detectors, and the system for synchronization of classical laser pulses. Methods of the invention use the embodiment of the apparatus summarized above to implement the objects of the invention. Importantly, the apparatus of the invention has communication efficiency that scales polynomially with channel length.

Additional physical systems that may be used for ensembles of the invention

include ensembles of atoms in similar potential energy traps, such as atoms in an ion trap, optical lattice position, or crystal lattice position, and which have collective excitations that they may couple to photons, such as phonon excitations in solids. Preferably, these atomic systems have energy levels similar to the Lambda-level structure such their collective excitations can be coupled to flying qubits in the same matter ans for alkali metal atoms. Additionally, ensembles of localized excitation states such as electron states in superlattice structures including quantum dot ensembles, and Bose-Einstein condensates, may be useful ensembles for implementing the invention.

A first method uses preferred embodiment of the apparatus which is modified to extend quantum communication distance by means of entanglement swapping.

An embodiment for implementing a second method of the invention comprises a source, four atomic ensembles, two beam splitters, four single count photo detectors, and two phase shifts. Additional elements comprise a synchronizer and single count photo detectors control system. Four atomic ensembles form two pairs of entangled atomic ensembles. A second method uses preferred embodiment of the apparatus which is modified to be efficiently used in the quantum communication protocols, such as quantum cryptography, and for Bell inequality detection.

An embodiment for implementing a third method of the invention comprises a source, six atomic ensembles, two beam splitters, and four single count photo detectors. Additional elements comprise a synchronizer and single count photo detectors control system. Six atomic ensembles form two pairs of entangled atomic ensembles and two pairs of atomic ensembles with collective atomic excitations. A third method uses preferred embodiment of the apparatus which is modified for realization of the quantum teleportation of the atomic polarization state.

This invention relies upon collective rather than single particle excitations in atomic ensembles. It provides entanglement connection using simple linear optical operations, and it is inherently robust against the realistic imperfections. Here, entanglement connection means that two objects are connected through entangled systems. Consider Fig. 2 (described in more detail below), given two separate entangled bipartite systems. That is to say, the two pairs (L, I1) and (R, I2) where the subsystem L is entangled with sybsystem I1 and subsystem R is entangled with subsystem I2. There is a way to create an entangled state between the two subsystems L and R. Such a process is generally called entanglement connection. A simple

example of entanglement connection is called entanglement swapping. Entanglement swapping is done by performing a so-called Bell-measurement between the two other systems I1 and I2. A successful Bell-measurement will connect the two subsystems L and R into an entangled state. In linear optics, it is often the case that a Bell-measurement can be successfully performed only probabilistically. A method to implement such a probabilistic Bell-measurement with linear optics and single-photon detectors of finite efficiency is shown in our Fig. 2.

Quantum communication protocols includes quantum teleportation, cryptography, and Bell inequality detection. Perfect entanglement means that interacting physical systems are fully correlated. Increasing communication length in embodiments of the present invention only increases overhead in the communication time polynomially.

The present invention can be implemented with only linear optical components such as beamsplitters and simple non-linear components such as imperfect single-photon detectors. Yet, it allows intrinsic fault-tolerance. The invention is probabilistic. Many of the sources of errors do not affect the resulting state, even though they affect the probability of success. Some of the errors only effect the coefficients of the successful state. Such modified coefficients can be easily compensated for or taken into account by system design without affecting polynomial scaling. Thus, one advantage of the present invention is that it allows the distribution of long distance quantum communication or entanglement with resources that only scale polynominally with the communication distance.

The invention also provides stable local information carriers, i.e, stable quantum memory, due to the stability of collective excitations, resulting in relatively long decoherence times. In addition, relatively large cross sections exist between certain photons and certain collective excitations use of which provides a substantial probability of collective excitation generation, per incident photon. These probabilities can be as great as approaching 1, preferably at least 0.5 less preferably 0.25 or 0.1.

The inventors recognized that the source may excite a number of other optical modes besides the desirable collective mode to be discussed below. The effects of those other optical modes can be computed by standard perturbation theory in quantum mechanics. Therefore, it is simplest to understand the invention by focusing on the desirable collective mode only. For this reason, a one-dimensional light

propagation model and only the desirable collective mode are discussed herein below, and all other optical modes are ignored. However, the invention applies to more general configurations and in the presence of other optical modes.

BRIEF DESCRIPTION OF THE FIGURES

Embodiments of the invention will be described in conjunction with the following figures in which like or corresponding elements are given the same identification.

Fig. 1 is a schematic of a novel apparatus of an embodiment of the present invention;

Fig. 2 is a schematic of a novel apparatus of another embodiment of the invention for performing entanglement swapping of the invention;

Fig. 3 is a schematic of a novel apparatus of another embodiment for realizing quantum cryptography and Bell inequality detection; and

Fig. 4 shows a schematic setup of an apparatus of the invention for performing probabilistic quantum teleportation of the atomic polarized state.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

An embodiment of an apparatus of the present invention comprises a light source, two cells each with a gas sample of atomic ensembles of atoms with a Lambda level configuration (examples are alkali atoms such as Sodium, Rubidium and Cesium), two filters, two channels, a beam splitter and two photodetectors, as shown in Fig. 1.

Fig. 1 shows apparatus 1 including a source 10, a source light pulse synchronizer 20, a light beams 30, 40, atomic ensemble cells 50, 60 (containing ensembles L, R), filters 70, 80, light beams 90, 100, channels 110, 120, stokes pulses 130, 140, beam splitter 150, stokes pulses 160, 170, single photon photo detectors 180, 190, and photo detector control system 200. Atomic ensembles 50, 60 each comprise a cell of an alkali gas sample. Source 10 comprises a coherent or incoherent light source.

Source 10 may include a pulser or amplitude modulator to convert continuous light to pulsed light. Source 10 may include electronics for synchronizing laser pulses. Source 10 emits either continuous light or pulses of light.

Cells 50, 60 each contain atomic ensembles L, R that can emit Stokes light

pulses in response to illumination by synchronized laser pulses. Each cell contains an alkali gas sample containing about $10^{\wedge 12}$ atoms of an alkali element. The cells are glass cells with antireflection inside coating. To facilitate enhanced coupling to light, the atomic medium is preferably optically thick along one direction. This can be easily achieved by working with a pencil shaped atomic sample.

Filters 70, 80 are structured to select (i.e., not reflect) specified polarization and frequency of light propagating from cells 50, 60, and to reject (i.e., reflect) non-selected polarization and frequency light propagating from cells 50, 60.

Transmission channels 110, 120 are structures, such as fiber optic, through which light transmitted through filters 70, 80 may propagate.

Beam splitter 150 is preferably a mirror that provides 50 percent incident intensity reflection and transmission. In alternative embodiments, beam splitter 150 may be replaced by a 50: 50 fiber coupler.

Single photon photo detectors 180, 190 are conventional detectors capable of detecting light propagated along paths 160, 170 from beam splitter 150.

Channels 110, 120 convey the Stokes light pulses from filters to beam splitter 150. Beam splitter 150 interferes the Stokes light pulses with a 50%-50% ratio.

That is, the beam splitter provides for interference of the two Stokes light pulses. It's function is therefore that of an interferer.

Single photon photo detectors 180, 190 detect pulses received from beam splitter 150.

Additional elements system 1 include electronics for controlling single photon photo detectors 180, 190, and electronics of source 10 for synchronizing laser pulses.

In operation, source 10 generates synchronized laser pulses propagating along paths 30, 40, into cells 50, 60. Stokes light pulses are emitted from the atomic ensembles in cells 50, 60, in response to illumination by the synchronized laser pulses. For the generation of entanglement using Stokes light pulses generated in the cells, the source must operate at the wavelength which matches the transition frequency of the atoms of the corresponding alkali element which forms the gas sample in the cell. Sources that can match the transition frequency of alkali atoms in cells 50, 60 include certain coherent and partially coherent source, such as certain solid state, semiconductor, dye, free electron, and gas lasers.

In one preferred embodiment, source 10 is a diode laser emitting pulses at a wavelength of 852 nm with pulse duration of 0.1 microsecond and typical repetition

rate of at least 1 MHz. This wavelength matches the absorption energy of Cesium atom ensembles at approximately room temperature, of 852 nm. Approximately room temperature in this context means temperatures between about 20 and about 30 Celsius. Preferably, each cell 50, 60 contains a cloud of approximately N identical alkali atoms.

Preferably, the atomic ensembles L, R in cells 50, 60 comprise atoms having a Lambda-level structure. For instance, Rubidium atoms vapor at around 70 to 90 degree Celsius, with atomic densities of about 10^{11} to 10^{12} per cubic centimeter and a diode laser with a frequency close to its atomic level transition frequency. In one embodiment, the alkali atom ensembles are at low temperature. For instance, in one embodiment, approximately 11 million sodium atoms are cooled to about 0.9 micro-Kelvin, just above the critical temperature for Bose-Einstein condensation, the cell defines the atomic cloud to have a length of about 350 micro-meter in the longitudinal direction traveled by the light and about 55 micro-meter in the transverse directions, and a peak atomic density of about 11 atoms per cubic micro-meter. Atomic densities in the range of 1 to 100 atoms per cubic centimeter may be useful

A dimension of order 3 cm in the longitudinal direction of cell, 50, 60 is desirable. However, if a larger dimension is employed, one can increase the overall decoupling strength between the source signal and the atom ensemble. Depending on the identity and density of the atom employed, in some applications, a larger dimension of the cell may be desirable.

The relevant level structure of the atoms in the ensemble contains $|g\rangle$, the ground state, $|s\rangle$, the metastable state for storing a qubit, and $|e\rangle$, the excited state. The transition $|g\rangle \to |e\rangle$ is coupled by the classical laser with the Rabi frequency, and the forward scattering Stokes light comes from the transition $|e\rangle \to |s\rangle$. An off-resonant coupling with a large detuning Δ is assumed. The two ensembles are pencil shaped and illuminated by the synchronized classical laser pulses. The forward-scattering Stokes pulses are transmitted through polarization and frequency selective filters 70, 80, propagate through channels 110, 120 and interfere at 50%-50% beam splitter 150. Finally, single photons propagating through beam splitter 150 are detected in single photon detectors 180, 190. If there is a click in either detector 180

or 190, the process is finished and the entanglement is generated between the ensembles L and R. Otherwise, a repumping pulse is first applied to the transition $|s\rangle \rightarrow |e\rangle$ on the ensembles L and R to set the state of the ensembles back to the ground state $|0\rangle_a^L \otimes |0\rangle_a^R$, then the same classical laser pulses as in the first round are applied to the transition $|g\rangle \rightarrow |e\rangle$ and the forward-scattering Stokes pulses are detected again after the beam splitter. This process is repeated until finally there is a click in either the detector 180 or 190.

A pair of metastable lower states $|g\rangle$ and $|s\rangle$ corresponds e.g. to hyperfine or Zeeman sublevels of electronic ground state of alkali atoms. All the atoms are initially prepared in the ground state $|g\rangle$. A sample is illuminated by a short, off-resonant laser pulse that induces Raman transitions into the states $|s\rangle$. The forward-scattered Stokes light that is co-propagating with the laser is uniquely correlated with the excitation of the symmetric collective atomic mode S given by $S \equiv \left(1/\sqrt{N_a}\right)\sum_i |g\rangle_i \langle s|$, where the summation is taken over all the atoms in the ensemble. In particular, an emission of the single Stokes photon in a forward direction results in the state of atomic ensemble given by $S^\dagger |0_a\rangle$, where the ensemble ground state $|0\rangle_a \equiv \otimes_i |g\rangle_i$).

The light-atom interaction time t_Δ is short enough so that the mean photon number in the forward scattered Stokes pulse is much smaller than 1. An effective single-mode bosonic operator a can be defined for this Stokes pulse with the corresponding vacuum state denoted by $|0\rangle_p$. The whole state of the atomic collective mode and the forward-scattering Stokes mode is written in the following form:

$$|\phi\rangle = |0\rangle_a |0\rangle_p + \sqrt{p_c} S^\dagger a^\dagger |0\rangle_a |0\rangle_p + o(p_c), \tag{1}$$

where p_c is the small excitation probability and $o(p_c)$represents the terms with more excitations whose probabilities are equal or smaller than p^2_c. A fraction of light is

emitted in other directions due to the spontaneous emissions. However, whenever N is large, the contribution to the population in the symmetric collective mode from the spontaneous emissions is small. As a result there is a large signal-to-noise ratio for the processes involving the collective mode, which greatly enhances the efficiency of the present methods.

The methods of the invention generate entanglement between two distant ensembles L and R using the configuration shown in Fig. 1. Two laser pulses excite both ensembles simultaneously and the whole system is described by the state $|\phi\rangle_L \otimes |\phi\rangle_R$, where $|\phi\rangle_L$ and $|\phi\rangle_R$ are given by Equation (1) with all the operators and states distinguished by the subscript L or R. The forward scattered Stokes light from both ensembles is combined at the beam splitter and a photodetector click in either detector 180 or 190 measures the combined radiation from two samples, $a_+^\dagger a_+$ or $a_-^\dagger a_-$ with $a_\pm = (a_L \pm e^{i\phi} a_R)/\sqrt{2}$. Here, φ denotes an unknown difference of the phase shifts in the two-side channels. φ has an imaginary part to account for the possible asymmetry of the setup, which will also be corrected automatically. The asymmetry can be easily made very small, and φ is assumed real in the following. Conditional on the detector click, a_+ or a_- are applied to the whole state $|\phi\rangle_L \otimes |\phi\rangle_R$. This provides the projected state of the ensembles L and R being nearly maximally entangled with the form (neglecting the high-order terms o (p_C))

$$\left|\Psi_\varphi\right\rangle_{LR}^{\pm} = \left(S_L^\dagger \pm e^{i\varphi} S_R^\dagger\right)/\sqrt{2}\left|0_a\right\rangle_L \left|0_a\right\rangle_R \quad . \qquad (2)$$

The probability for getting a click is given by p_C for each round, so the process must be repeated about $1/p_C$ times for a successful entanglement preparation, and the average preparation time is given by $T_0 \sim t_\Delta / p_c$. The states $\left|\Psi_\varphi\right\rangle_{LR}^{+}$ and $\left|\Psi_\varphi\right\rangle_{LR}^{-}$ are easily transformed to each other by a local phase shift. Without loss of generality, it is assumed in the following that the entangled state $\left|\Psi_\varphi\right\rangle_{LR}^{+}$ is generated.

The presence of the noise modifies the projected state of the ensembles to

$$\rho_{LR}(c_0,\varphi)=\frac{1}{c_0+1}\left(c_0\left|0_a0_a\right\rangle_{LR}\left\langle 0_a0_a\right|+\left|\Psi_\varphi\right\rangle_{LR}^{+}\left\langle\Psi_\varphi\right|\right), \tag{3}$$

where the "vacuum" coefficient c_0 is determined by the dark count rates of the photon detectors. It will be seen below that any state in the form of Equation (3) will be purified automatically to a maximally entangled state in the entanglement-based communication schemes. Therefore this state is called an effective maximally entangled (EME) state with the vacuum coefficient c_0 determining the purification efficiency.

Each step of the process of entanglement generation and applications contains built-in entanglement purification which makes the method resilient to realistic noise and imperfections. In entanglement generation, the dominant noise is photon loss noise, which includes the contributions from the channel attenuation, the spontaneous emissions in the atomic ensembles (which results in the population of the collective atomic mode with the accompanying photon going to other directions), the coupling inefficiency of the Stokes light into and out of the channel, and the inefficiency of the single-photon detectors. The loss probability is denoted by $1-\eta_p$ with the overall efficiency $\eta_p=\eta_p' e^{-L_0/L_{att}}$, where the channel attenuation $e^{-L_0/L_{att}}$ is separated (L_{att} is the channel attenuation length) from other noise contributions with η_p' independent of the communication distance L_0. The photon loss decreases the success probability for getting a detector click from p_c to $\eta_p p_c$, but it has no influence on the resulting EME state. In this sense, the entanglement purification process is built-in and the process is intrinsically fault-tolerant. Due to this noise, the entanglement preparation time is replaced by $T_O \sim t_\Lambda / \eta_p p_p$. In non-technical terms, many types of errors are in some sense, "self-correcting" in the process. Note that the method of the invention is probablistic on the existence of a pulse detection, each outcome of an event is known to be either a "success" or a "failure" e.g. by the existence or non-existence of a pulse detection. Errors that are self-correcting affect the probability of success and the coefficients of the resulting states, but they do not, a priori, lead to a corrupted state, when the protocol indicates a "success" in the process. The change in coefficients in the process due to errors can be either pre-computed or observed in a real experiment. Therefore, those effects can be compensated or

accounted for without affecting the main spirit of the protocol, e.g., the ability to communicate. The built-in nature of entanglement purification and, thus, the intrinsic fault-tolerant nature of the entanglement purification process is discussed in more detail in subsequent paragraphs. In summary, the process of the invention has built-in entanglement purification and is intrinsically fault-tolerant.

The second source of noise comes from the dark counts of the single-photon detectors. The dark count gives a detector click, but without population of the collective atomic mode, so it contributes to the vacuum coefficient in the EME state. If the dark count comes up with a probability p_{dc} for the time interval t_Δ, the vacuum coefficient is given by $c_0 = p_{dc}/(\eta_p p_c)$, which is typically much smaller than 1 since the Raman transition rate is much larger than the dark count rate. The final source of noise, which influences the fidelity to get the EME state, is caused by an event in which more than one atom is excited to the collective mode S whereas there is only one click in either detector 180 or 190. The conditional probability for that event is given by p_c, so we can estimate the fidelity imperfection $\Delta F_0 \equiv 1 - F_0$ for the entanglement generation by

$$\Delta F_0 \sim p_c \qquad (4)$$

By decreasing the excitation probability p_c, it is possible to make the fidelity imperfection closer and closer to zero with the price of a longer entanglement preparation time T_0. This is the basic idea of the entanglement purification. In this scheme, the confirmation of the click from the single-photon detector generates and purifies entanglement at the same time.

In the entanglement swapping, the dominant noise is the losses, which include the contributions from the detector inefficiency, the inefficiency of the excitation transfer from the collective atomic mode to the optical mode, and the small decay of the atomic excitation during the storage. By introducing the detector inefficiency, the imperfection is automatically taken into account by the fact that detectors 180, 190 cannot distinguish between a single and two photons. The overall efficiency in the entanglement swapping is denoted by η_s. The loss in the entanglement swapping gives contributions to the vacuum coefficient in the connected EME state, since in the presence of loss a single detector click might result from two

collective excitations in the ensembles I_1 and I_2, and in this case, the collective modes in the ensembles L and R have to be in a vacuum state. After taking into account the realistic noise, it is possible to specify the success probability and the new vacuum coefficient for the i^{th} entanglement connection by the recursion relations $p_i = f_1(c_{i-1}) = \eta_s(1-\eta_s/2(c_{i-1}+1))/(c_i+1)$ and $c_i = f_2(c_{i-1}) = 2c_{i-1}+1-\eta_s$. The coefficient c_0 for the entanglement preparation is typically much smaller than $1-\eta_s$, then $c_i \approx (2^i-1)(1-\eta_s) = (L_i/L_0-1)(1-\eta_s)$, where L_i denotes the communication distance after i times entanglement connection. With the expression for the c_i, the probability p_i and the communication time T_n are evaluated for establishing an EME state over the distance $L_n = 2^n L_0$. After the entanglement connection, the fidelity of the EME state also decreases, and after n times connection, the overall fidelity imperfection $\Delta F_n \sim 2^n \Delta F_0 \sim L_n/L_0 \Delta F_0$. ΔF_n must be fixed to be small by decreasing the excitation probability p_c in Equation (4).

The entanglement connection scheme also has built-in entanglement purification function. This can be understood as follows: Each time entanglement is connected, the imperfections of the setup decrease the entanglement fraction $1/(c_i + 1)$ in the EME state. However, the entanglement fraction decays only linearly with the distance (the number of segments), which is in contrast to the exponential decay of the entanglement for the connection schemes without entanglement purification. The reason for the slow decay is that in each time of the entanglement connection, the protocol must be repeated until there is a detector click, and the confirmation of a click removes part of the added vacuum noise since a larger vacuum components in the EME state results in more repetitions. The built-in entanglement purification in the connection scheme is essential for the polynomial scaling law of the communication efficiency.

Entanglement applications of the invention also have built-in entanglement purification which makes them resilient to the realistic noise. Firstly, the vacuum components in the EME states are removed from the confirmation of the detector clicks and thus have no influence on the fidelity of all the application schemes. Secondly, if the single-photon detectors and the atom-to-light excitation transitions in the application schemes are imperfect with the overall efficiency, then these imperfections only influence the efficiency to get the detector clicks with the success probability replaced by

$p_a = \eta_a / \left[2(c_n+1)^2\right]$, and have no effects on the communication fidelity. Finally, the phase shifts in the stationary channels and the small asymmetry of the stationary setup are removed automatically when the EME state is projected onto the PME state, and thus have no influence on the communication fidelity. The noise not correctable by this method includes the detector dark count in the entanglement connection and the non-stationary channel noise and set asymmetries. The resulting fidelity imperfection from the dark count increases linearly with the number of segments L_n/L_0, and form the non-stationary channel noise and set asymmetries increases by the random-walk law $\sqrt{L_n L_0}$. For each time of entanglement connection, the dark count probability is about $10^{\wedge-5}$ if a typical choice is made that the collective emission rate is about 10 MHz and the dark count rate is 10^2 Hz. This noise is negligible even if for communications over a long distance (10^3 the channel attenuation length L_{att} for instance). The non-stationary channel noise and setup asymmetries can also be safely neglected for such a distance. For instance, it is relatively easy to control the non-stationary asymmetries in local laser operations to values below 10^{-4} with the use of accurate polarization techniques for Zeeman sublevels.

In some formulas in this specification, the "proportional to" sign (~) is replaced by a box symbol, such as □, which also means "proportional to" herein.

Each of the entanglement generation, connection, and application methods of the invention has built-in entanglement purification. As a result of this property, the communication fidelity can be fixed to be nearly perfect, and the time for preparing the system for communication increases only polynomially with the distance. To communicate over a distance $L = L_n = 2^n L_0$ the overall fidelity imperfection must be fixed to be a desired small value ΔF_n, in which case the entanglement preparation time is

$T_0 \,\square\, t_\Delta / (\eta_p \Delta F_0) \,\square\, (L_n / L_0) t_\Delta / (\eta_p \Delta F_n)$. For an effective generation of the PME state, the total communication time $T_{tot} \,\square\, T_n / p_a$ with $T_n \,\square\, T_0 \prod_{i=1}^{n} (1/p_i)$. The total communication time scales with the distance by the law

$$T_{tot} \,\square\, 2(L/L_0)^2 / \left(\eta_p \eta_a \Delta F_T \prod_{i=1}^{n} p_i\right) \qquad (5)$$

where the success probabilities p_i, p_a for the i^{th} entanglement connection and for the entanglement application have been specified before. The expression (5) confirms that the

communication time T_{tot} increases with the distance L only polynomially. In the first limiting case, the inefficiency $1-\eta_s$ for the entanglement swapping is assumed to be negligibly small. It is deduced from Equation (5) that in this case the communication time $T_{tot} \square T_{con} \left(L/L_0\right)^2 e^{L_0/L_{att}}$, with the constant $T_{con} = 2t_\Delta / \left(\eta'_p \eta_a \Delta F_T\right)$ being independent of the segment and the total distances L_0 and L. The communication time T_{tot} increases with L quadratically. In the second case, it is assumed that the inefficiency $1-\eta_s$ is considerably large. The communication time in this case is approximated by $T_{tot} \square T_{con} \left(L/L_0\right)^{[\log_2(L/L_0)+1]/2+\log_2(1/\eta_s-1)+2} e^{L_0/L_{att}}$, which increases with L still polynomially (or sub-exponentially in a more accurate language, but this makes no difference in practice since the factor $\log_2 (L/L_0)$ is well bounded from above for any reasonably long distance). If T_{tot} increases with L/L_0 by the power law $(L/L_0)^m$, there is an optimal choice of the segment length to be $L_0 = mL_{att}$ to minimize the time T_{tot}. As an estimation of the improvement in the communication efficiency, it is assumed that the total distance L is about $100L_{att}$, for a choice of the parameter $\eta_s \approx 2/3$, the communication time $T_{tot}/T_{con} \sim 10^6$ with the optimal segment length $L_0 \sim 5.7L_{att}$. This result is a dramatic improvement compared with the direct communication case, where the communication time T_{tot} for getting a PME state increases with the distance L by the exponential law $T_{tot} \square T_{con} e^{L/L_{att}}$. For the same distance L $\sim 100L_{att}$, one needs $T_{tot}/T_{con} \sim 10^{43}$ for direct communication, which means that for this example the present scheme is 10^{37} times more efficient.

Fig. 2 shows system 201 including source 10, synchronizer 20, cells 230, 231 of atomic ensembles I1, I2, cells 241, 242 of atomic ensembles L, R, light paths 250, 251, filters 260, 261, beam splitter 270, single photon detectors 280, 281, and photo detector control system 290. In addition, Fig. 2 shows unscattered light paths 252, 253, and stokes light paths 254, 255.

Concurrent light pulses transmitted from source 10 traverse paths 250, 251 to ensembles I1, I2 in cells 230, 231. In ensembles I1, I2, light pulse photons either undergo a collective stokes scattering of the atoms of the ensemble or they do not. If they do not, they are reflected by filters 260, 261 along paths 252, 523. If they are Stokes scattered, they are converted to different frequency (and/or k vector) allowing filters 260, 261 to distinguish them from non-scattered light. The Stokes scattered light pulses are transmitted along paths 254, 255, and then interfere at beam splitter 270. Detectors 280, 281 receive pulses propagating along paths 254,

255, and each detector generates a detection signal when it detects a pulse. Photo detector control system 290 controls detectors 280, 290, and receives detection signals from detectors 280, 281.

Fig. 2 shows two pairs of ensembles L, I1 and I2, R and four sites. Each of the ensemble-pairs pair L, I1 and pair I2 , R is prepared in an EME state in the form of Equation (3). The excitations in the collective modes of the ensembles I1 and I2 are transferred simultaneously to the optical excitations by the repumping pulses applied to the atomic transition $|s\rangle \rightarrow |e\rangle$, and the stimulated optical excitations, after a 50%-50% beam splitter, are detected by the single-photon detectors 180 and 190. If either detector 180 or 190 clicks, the protocol is successful and an EME state is established between the ensembles L and R thereby doubling effective communication distance. If no detector clicks, the previous entanglement generation and swapping is repeated until finally there is a click in detector 180 or 190, that is, until the protocol succeeds.

The two intermediated ensembles I1 and I2 can be replaced by one ensemble having two metastable states to store two different collective modes. The 50%-50% beam splitter operation can be replaced by its functional equivalent, a so-called pi /2 pulse. In the language of quantum field theory, let the collective modes be described by the two collective mode annihilation operators, a_1 and a_2. Such a pi/2 pulse maps a_1 and a_2 into their linear combinations in the following manner: a_1 into { 1 over square root of 2} (a_1 + i a_2) and a_2 into {1 over square root of 2} (a_1 - i a_2) - Eq. (A). Physically, such a pi/2 pulse may be implemented by an external laser (not shown in Fig. 2) that emits a pulse onto the the ensemble containing the two said metastable states. The ensemble absorbs the pi/2 laser pulse and changes its own state according to the transformation of the two said collective mode annihilation operators described by Eq. (A).

The embodiment in Fig. 2 provides two pairs of the entangled ensembles described by the state $\rho_{LI_1} \otimes \rho_{I_2R}$, where ρ_{LI_1} and ρ_{I_2R} given by Equation (3). In the ideal case, the setup shown in Fig. 2 measures the quantities corresponding to operators $S_\pm^\dagger S_\pm$ with $S_\pm = \left(S_{I_1} \pm S_{I_2}\right)/\sqrt{2}$. If the measurement is successful (i.e., one of the detectors registers one photon), the ensembles L and R are prepared into another EME state.

The new φ-parameter is given by $\varphi_1 + \varphi_2$, where φ_1 and φ_2 denote the old φ-

parameters for the two segment EME states. In the presence of the realistic noise and imperfections, an EME state is still created after a detector click. Noise only influences the success probability to get a click and the new vacuum coefficient in the EME state. In general the success probability p_1 is expressed and the new vacuum coefficient c_1 as $p_1 = f_1(c_0)$ and $c_1 = f_2(c_0)$, where the functions f_1 and f_2 depend on the particular noise properties.

The above method for connecting entanglement can be cascaded to arbitrarily extend the effective communication distance. For the i^{th} ($i = 1, 2,\ldots, n$) entanglement connection, two pairs are first prepared in parallel of ensembles in the EME states with the same vacuum coefficient c_{i-1} and the same communication length L_{i-1}, and entanglement swapping as shown in Fig. 2 is performed. This entanglement swapping attempt succeeds with a probability $p_i = f_1(c_{i-1})$. After a successful detector click, the communication length is extended to $L_i = 2L_{i-1}$, and the vacuum coefficient in the connected EME state becomes $c_i = f_2(c_{i-1})$. Since the i^{th} entanglement connection need be repeated in average $1/p_i$ times, the total time needed to establish an EME state over the distance $L_n = 2^n L_0$ is given by $T_n = T_0 \prod_{i=1}^{n}(1/p_i)$, where L_0 denotes the distance of each segment in the entanglement generation.

Entanglement can attempted at a rate up to the pulse rate of source 10. Typically available sources operate up to the megahertz frequencies. In principle, pulse rates in the gigahertz frequencies are attainable, and would result in a time T_0 of sub nanoseconds. Therefore, the average total time needed to establish entanglement in a system of a relatively large number of ensembles can be shorter than a micro second.

In a second method of the invention, the EME is used in the communication protocols, such as quantum teleportation, cryptography, and Bell inequality detection. Fig. 3 shows the schematic setup for the realization of quantum cryptography.

Fig. 3 schematically shows system 301 including source 10, synchronizer 20, cells 330, 331, containing atomic ensembles L1, R1, cells 340, 341 containing atomic ensembles L2, R2, beam splitters 350, 351, phase shifters 360, 361, photo detectors 380, 381, photo detectors 390, 391, and photo detector control system 390.

Fig. 3 shows an embodiment in long-distance quantum key distribution or in testing of Bell inequalities. In Fig. 3, two pairs of atom ensembles (L1, R1) and (L2,R2) are shown. Each pair, for example, (L1,R1) can be the result of a concatenated application of Fig. 2

(entanglement swapping and entanglement purification) discussed in preceding paragraphs. Additional laser sources and any synchronization systems are probably needed to set up the initial state of (L1,R1) and also (L2,R2). However, since those additional elements have been discussed in preceding paragraphs concerning Fig. 2, we will leave them out from Fig. 3 and assume that the preparation of the initial states of (L1,R1) and (L2,R2) has already been performed. Formally, the state of the pair, say (L1, R1), is described as an EME state defined earlier. The arrow 385 indicates the fact that the pair (L1,R1) has been prepared in an EME state and is, thus, quantum mechanically correlated with entanglement. Similarly, the arrow 386 indicates that the fact that the pair (L2,R2) has been prepared an EME state and is, thus, quantum mechanically correlated with entanglement. In Fig. 3, each pair (L1, R1) may be separated spatially by a very long distance, say 100, 1000, or even 10,000 km. However, L1 and L2 are supposed to be spatially located much closer than the distance between L1 and R1. A typical distance between L1 and L2 may be 10 m or less, although a much longer distance of say one km may also be acceptable. Similarly, R1 and R2 are supposed to be spatially located much closer than the distance between L1 and R1. Two pairs of atom ensembles are needed because a pair of photons are needed for an experiment in quantum key distribution whereas a pair of atom ensemble typically gives out only a single photon. The beam-splitters 350 and 351 allow us to entangle the two pairs of atom ensembles, thus generating a maximally entangled state between them. In our preferred embodiment, the detector/control system consists of two separate detector/control subsystems located near to (L1,L2) and (R1,R2) respectively. The detector/control subsystem that is located near to (L1,L2) controls the setting of the phase shifter 360 and, thus, decides on the type of measurement to be performed on the systems (L1,L2). Similarly, the detector/control subsystem that is located near to (R1,R2) controls the setting of the phase shifter 361 and decides on the type of measurement to be performed on the systems (R1,R2). The output to the experiment is given by how many and which of the single-photon photo-detectors 370, 371, 380 and 381 have detected a photon.

As schematically shown in Fig. 3, one optical pulse path traverses in sequence ensembles L1 and L2. Another optical pulse path traverses ensembles R1 and R2. Photons generated by the desired collective excitations in either L1 or L2 propagate to beam splitter (interferer) 350. The angles shown between photon paths into ensembles and photon paths from ensembles to beam splitters 350, 351 are drawn for convenience of illustration. For example, the photons generated by collective excitations in an ensemble may propagate in the same direction as incident photons, and subsequently be diverted by a wavelength dependent reflector disposed on a far side of the ensemble. Detection at detector 370 or 371 indicates a

collective excitation in (L1,L2), which indicates that L2,R2 is entangled with L1,R1. A more detailed and more mathematical description of Fig. 3 is as follows:

Two pairs of ensembles, pair L1, R1 and pair L2, R2 (or two pairs of metastable states) are each prepared in EME states. The collective atomic excitations on each side are transferred to the optical excitations, which, respectively after a relative phase shift φ_L or φ_R and a 50%-50% beam splitter, are detected by the single-photon detectors D_1^L, D_1^L and D_1^R, D_2^R. There are four possible coincidences of D_1^R, D_2^R with D_1^L, D_1^L, which are functions of the phase difference $\varphi_L - \varphi_R$. Depending on the choice φ_L and φ_R, this setup can realize both the quantum cryptography and the Bell inequality detection.

It is not obvious that the EME state (3), which is entangled in the Fock basis, is useful for these tasks since in the Fock basis it is experimentally hard to do certain single-bit operations. EME states can be used to realize all these protocols with simple experimental configurations.

The state of the two pairs of ensembles is expressed as $\rho_{L_1R_1} \otimes \rho_{L_2R_2}$, where $\rho_{L_iR_i}$ $(i = 1,2)$ denote the same EME state with the vacuum coefficient c_n if entanglement connection has been done n times. The φ -parameters in $\rho_{L_iR_i}$ $(i = 1,2)$ are the same provided that the two states are established over the same stationary channels. Only the coincidences of the two-side detectors are registered, so the protocol is successful only if there is a click on each side. Under this condition, the vacuum components in the EME states, together with the state components $S_{L_1}^\dagger S_{L_2}^\dagger |vac\rangle$ and $S_{R_1}^\dagger S_{R_2}^\dagger |vac\rangle$, where $|vac\rangle$ denotes the ensemble state $|0_a 0_a 0_a 0_a\rangle_{L_1R_1L_2R_2}$, have no contributions to the experimental results. So, for the measurement scheme shown by Fig. 3, the ensemble state $\rho_{L_1R_1} \otimes \rho_{L_2R_2}$ is effectively equivalent to the following "polarization" maximally entangled (PME) state

$$|\psi\rangle_{PME} = \left(S_{L_1}^\dagger S_{R_2}^\dagger + S_{L_2}^\dagger S_{R_1}^\dagger\right)/\sqrt{2}\,|vac\rangle \qquad (6)$$

The success probability for the projection from $\rho_{L_1R_1} \otimes \rho_{L_2R_2}$ to $|\Psi\rangle_{PME}$ (i.e., the probability to get a click on each side) is given by $p_a = 1/\left[2\left(c_n+1\right)^2\right]$. In Fig. 3, the phase

shift ψ_Λ $(\Lambda = L\, or\, R)$ together with the corresponding beam splitter operation are equivalent to a single-bit rotation in the basis $\left\{|0\rangle_\Lambda = S^\dagger_{\Lambda_1}|0_a 0_a\rangle_{\Lambda_1\Lambda_2}, |1\rangle_\Lambda = S^\dagger_{\Lambda_2}|0_a 0_a\rangle_{\Lambda_1\Lambda_2}\right\}$ with the rotation angle $\theta = \psi_\Lambda / 2$. Now, there is the PME state and it is possible to perform the desired single-bit rotations in the corresponding basis, and thus to implement quantum cryptography and Bell inequality detection. For instance, to distribute a quantum key between the two remote sides, we simply choose ψ_Λ randomly from the set $\{0, \pi/2\}$ with an equal probability, and keep the measurement results (to be 0 if D_1^L clicks, and 1 if D_1^R clicks) on both sides as the shared secret key if the two sides become aware that they have chosen the same phase shift after the public declare. This is exactly the Ekert scheme and its absolute security is already proven. For the Bell inequality detection, we infer the correlations

$E(\psi_L, \psi_R) = P_{D_1^L D_1^R} + P_{D_2^L D_2^R} - P_{D_1^L D_2^R} - P_{D_2^L D_1^R} = \cos(\psi_L - \psi_R)$ from the measurement of the coincidences $P_{D_1^L D_1^R}$, etc. For the setup shown in Fig. 3, the output is

$\left|E(0,\pi/4) + E(\pi/2,\pi/4) + E(\pi/2,3\pi/4) - E(0,3\pi/4)\right| = 2\sqrt{2}$ whereas for any local hidden variable theories this value should be below 2.

A third method of using the preferred embodiment realizes the setup for probabilistic quantum teleportation of the atomic "polarization" state. Similarly to the second method, two pairs of ensembles L_1, R_1 and L_2, R_2 are prepared in the EME states. An atomic "polarization" state $(d_0 S^\dagger_{I_1} + d_1 S^\dagger_{I_2})|0_a 0_a\rangle_{I_1 I_2}$ can be teleported with unknown coefficients d_0, d_1 from the left to the right side, where $S^\dagger_{I_1}$, $S^\dagger_{I_2}$ denote the collective atomic operators for the two ensembles I_1 and I_2 (or two metastable states in the same ensemble). The collective atomic excitations in the ensembles I_1, L_1 and I_2, L_2 are transferred to the optical excitations, which, after a 50%-50% beam splitter, are detected by the single-photon detectors D_1^I, D_1^L and D_2^I, D_2^L. If there are a click in D_1^I or D_1^L and a click in D_2^I or D_2^L, the protocol is successful. A π-phase rotation is then performed on the collective mode of the ensemble R_2 conditional on that the two clicks appear in the detectors D_1^I, D_2^L or D_2^I, D_1^L. The collective excitation in the ensembles R_1 and R_2, if appearing, would be found in the same "polarization" state

$(d_0 S_{R_1}^{\dagger} + d_1 S_{R_2}^{\dagger})|0_a 0_a\rangle_{R_1 R_2}$.

The established long-distance EME states can be also used for faithful transfer of unknown quantum states through quantum teleportation, with the setup shown by Fig. 4.

Fig. 4 schematically shows system 401 including secondary control system 495, communication link 496, optical pulse channels 497, 498, cells 430, 431, cells 440, 441, and cells 442, 443, beam splitters 450, 451, single photon detectors 470, 471, and 480, 481, and photo detector control system 490.

In operation of the Fig. 4 embodiment, photo detector control system 490 receives detection signals from single photon detectors 470, 471, and 480, 481. Based upon that data, photo detector control system 490 sends optical pulse generation control data via communication link 496 to secondary control system 495. Based upon that optical pulse generation control data, secondary control system 495 controls an optical source's generation of optical pulses for transmission to ensemble R1 or ensemble R2. The two headed arrow between ensembles R1,L1 indicate that those two ensembles are initially entangled. The two headed arrow between ensembles R2,L2 indicate that those two ensembles are initially entangled.

Fig. 4 shows an embodiment for probabilistic quantum teleportation. Consider the atom ensembles (L1, R1) and (L2,R2) shown in Fig. 4. Each pair, for example, (L1,R1) can be the result of a concatenated application of Fig. 2 (entanglement swapping and entanglement purification) discussed in preceding paragraphs. Additional laser sources and any synchronization systems are probably needed to set up the initial state of (L1,R1) and also (L2,R2). However, since those additional elements have been discussed in preceding paragraphs concerning Fig. 2, we will leave them out from Fig. 4 and assume that the preparation of the initial states of (L1,R1) and (L2,R2) has already been performed. Formally, the state of a pair, say (L1, R1), is described as an EME state defined earlier. Arrow 485 indicates the fact that the pair (L1,R1) has been prepared in an EME state and is, thus, quantum mechanically correlated with entanglement. Similarly, arrow 486 indicates that the fact that the pair (L2,R2) has been prepared an EME state and is, thus, quantum mechanically correlated with entanglement. In Fig. 4, each pair (L1,R1) may be separated spatially by a very long distance, say 100, 1000, or even 10,000 km. However, L1 and L2 are supposed to be spatially located much closer than the distance between L1 and R1. A typical distance between L1 and L2 may be 10 meters or less, although a much longer distance of say one km may also be acceptable. Similarly, R1 and R2 are supposed to be spatially located much closer than the

distance between L1 and R1. Note that two pairs of atom ensembles are needed because the experiment concerns a state of a pair of polarization entangled photons whereas a pair of atom ensembles typically gives out only a single photon.

In Fig. 4, the pair of atom ensemble (I1,I2) is in some unknown quantum state. The goal of Fig. 4 is to teleport this unknown state from (I1,I2) to the right hand side (R1,R2). Here, I1 is located spatially close to L1 and I2 spatially close to L2. A typical distance between I1 and L1 may be 10 meters or less, although a much longer distance of say one km may also be acceptable. Similarly, for I2 and L2. Here, a photodetector/control system 490 can be used for controlling the photo detectors 470, 471, 480 and 481. Effectively, (L1,L2) constitutes a logical qubit (call it qubit A) and (I1,I2) constitutes an unknown input qubit (call it qubit E). In Fig. 4, a probabilistic Bell-measurement is performed on the joint system of the above said qubits (A,E). The pair (R1,R2) represents a third qubit, call it qubit B. Control system 490 obtains the outcome of the probabilistic Bell-measurement and sends it via the communication link 496 to the secondary control system 495. Conditional on the outcome it has received, the secondary control system 495 may apply one out of a plurality of operations on the systems, R1 and R2, via the control lines, 497 and 498, to regenerate the state of teleported qubit (qubit E). In other words, after the re-generation, the state of the qubit B, which is stored in the physical system of the pair (R1,R2), now becomes the state of the original qubit E. Therefore, the quantum signal has been sent over long distances of potentially 100, 1000 or even 10000 km.

The mathematical and more detailed description of Fig. 4 is as follows:

In this setup, if two detectors click on the left side, there is a significant probability that there is no collective excitation on the right side since the product of the EME states $\rho_{L_1R_1} \otimes \rho_{L_2R_2}$ contains vacuum components. However, if there is a collective excitation appearing from the right side, its "polarization" state would be exactly the same as the one input from the left. The teleportation here is probabilistic and needs posterior confirmation; but if it succeeds, the teleportation fidelity would be nearly perfect since in this case the entanglement is equivalently described by the PME state (6). The success probability for the teleportation is also given by $p_a = 1/\left[2\left(c_n+1\right)^2\right]$, which determines the average number of repetitions for a successful teleportation.

The foregoing describes the theory of the invention and practical applications based upon collective excitation of a correlated system of alkali atoms, and provides some specific

examples of systems for using the invention for signal communication. However, the inventors recognize that collective excitations in many other correlated systems exist, that many of those excitations may be found suitable for use as a correlated system of the invention instead of the atomic ensembles noted in the foregoing examples. Thus, while only certain features of the present invention have been outlined and described herein, many modifications and variations will be apparent to those skilled in the art. Therefore, the claims appended hereto are intended to cover all such modifications and equivalents that fall within the broad scope of the invention.